Production asymmetry of D mesons in γp collisions *

G. Herrera A. Sánchez-Hernández
Centro de Investigación y de Estudios Avanzados
Apdo. Postal 14 740, México 07000, D.F.

E. Cuautle, J. Magnin
Centro Brasileiro de Pesquisas Físicas
Rua Dr. Xavier Sigaud 150
22290-180, Rio de Janeiro, Brazil

Abstract

We study the production asymmetry of charm versus anticharm mesons in photon-proton interactions. We consider photon gluon fusion plus higher order corrections in which light quarks through vector meson -proton interactions contribute to the cross section. Non perturbative effects are included in terms of a recombination mechanism which gives rise to a production asymmetry.

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1 Introduction

In high energy photon-hadron interactions, charm production is expected to be dominantly produced by photon-gluon fusion processes. According with QCD perturbative calculations, this mechanism produces in equal amounts charm and anti-charm.
However, recent measurements of charm meson production [1] indicate that there are important nonperturbative QCD phenomena in the production process that induce an asymmetry in charm and anti-charm production.
This phenomena has been observed in hadron hadron collisions [2] and is well known as "leading effect". It has been the subject of many models of particle production and several mechanisms have been proposed to explain it [1, 3, 4]. Here we study the x_F distribution of $D^{\pm}$ and D^0 mesons produced in photon-proton collisions in the framework of a two-components model that has been used before to successfully describe the asymmetry in pion proton interactions [4].

The production of D mesons in the model is assumed to take place *via* two different processes, namely QCD parton fusion with the subsequent fragmentation of quarks in the final state and conventional recombination of valence and sea quarks present in a vector meson fluctuation of the photon.
The asymmetries obtained with the conventional soft charm component as well as with a hard charm component in the photon, are presented. We compare both with the experimental data available.

To quantify the difference in the production of charm and anti-charm mesons an asymmetry A is defined as in [1],

$$A(x_F, p_t) = \frac{N_c - N_{\bar{c}}}{N_c + N_{\bar{c}}}. \tag{1}$$

where N_c and $N_{\bar{c}}$ are the production yields. The asymmetry has been observed to be a function of both x_F and the transverse momentum p_t.

This paper is organized as follows: the photon gluon mechanism for charm production will be discussed in section 2. This mechanism is not responsible of a production asymmetry between charm and anti-charm. In section 3 we discuss the contribution of the resolved photon in the frame of a Vector Dominance Model (VDM) component. In subsection 3.1 we calculate the QCD interaction of the resolved photon. In subsection 3.2, a recombination mechanism is discussed. While the QCD production mechanisms in photoproduction are the same for charm and anti-charm production, recombination favors the formation of D^- over D^+ and $\bar{D}^0$ over D^0. In section 4 the various components are put together and the asymmetry is estimated. Finally some conclusions are drawn in section 5.

2 The photon-gluon fusion mechanism

In this section we outline the calculation of the photon-gluon fusion contribution at Leading Order (LO) in pQCD to the D-meson inclusive x_F distribution.

The processes involved in the photoproduction of charm at LO in pQCD are depicted in Fig. 1. The corresponding formula in the parton model is

$$E_c E_{\bar{c}} \frac{d\sigma}{d^3p_c d^3p_{\bar{c}}} = \int_0^1 dx\; g(x,Q^2) E_c E_{\bar{c}} \frac{d\hat{\sigma}}{d^3p_c d^3p_{\bar{c}}} \tag{2}$$

where $g(x,Q^2)$ is the gluon probability density in the proton and

$$E_c E_{\bar{c}} \frac{d\hat{\sigma}}{d^3p_c d^3p_{\bar{c}}} = \frac{1}{2\hat{s}} \frac{\alpha_e \alpha_s(Q^2)}{4(2\pi)^6} (2\pi)^4 \delta(p_\gamma + p_g - p_c - p_{\bar{c}}) \left|M\right|^2 \ . \tag{3}$$

The squared invariant matrix $\left|M\right|^2$ in terms of the Mandelstam variables is given by (see e.g. [5, 6])

$$\left|M\right|^2 = \frac{8}{9}\left[\frac{1}{2}\left(\frac{m_c^2-\hat{t}}{m_c^2-\hat{u}} + \frac{m_c^2-\hat{u}}{m_c^2-\hat{t}}\right) + 2\left(\frac{m_c^2}{m_c^2-\hat{t}} + \frac{m_c^2}{m_c^2-\hat{u}}\right) - 2\left(\frac{m_c^2}{m_c^2-\hat{t}} + \frac{m_c^2}{m_c^2-\hat{u}}\right)^2\right] \tag{4}$$

and

$$\begin{aligned} \hat{s} &= xs \\ \hat{t} &= m_c^2 - m_T\sqrt{s}e^{-y_c} \\ \hat{u} &= m_c^2 - x m_T \sqrt{s} e^{y_c} \ , \end{aligned} \tag{5}$$

where s is the c.m energy of the $\gamma - p$ system, $m_T^2 = m_c^2 + p_T^2$, x is the momentum fraction of the gluon inside the proton and $y_c = (1/2)\, ln[(E_c - p_c)/(E_c + p_c)]$ the rapidity of the c-quark.

After integrating out Eq. 2 on the $\bar{c}$-quark variables and the momentum fraction x, the inclusive cross section for the production of charm (anti-charm) is given by

$$\frac{d\sigma}{dx_F} = \frac{\sqrt{s}}{2} \int dp_T^2 \frac{x g(x,Q^2)}{E(\sqrt{s} - m_T e^{y_c})} \frac{d\hat{\sigma}}{d\hat{t}} \tag{6}$$

with

$$\begin{aligned} \frac{d\hat{\sigma}}{d\hat{t}} &= \frac{\pi \alpha_e \alpha_s(Q^2)}{\hat{s}^2} \left|M\right|^2 \\ x &= \frac{m_T e^{-y_c}}{\sqrt{s} - m_T e^{y_c}} \ . \end{aligned} \tag{7}$$

In Eq. 7, α_s is given by

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2N_f) log\frac{Q^2}{\Lambda^2}} \tag{8}$$

with $N_f = 4$ and $\Lambda^2 = \Lambda_4^2$ according to the gluon distribution used in Eq. 6.

In our calculations we use the GRV-LO gluon distribution [7] with $Q^2 = 4m_c^2$, $m_c = 1.5$ GeV. The D-meson inclusive x_F distribution including fragmentation is given by

$$\begin{aligned} \frac{d\sigma_D}{dx_F} &= \int \frac{dz}{z} \frac{d\sigma_{c(\bar{c})}}{dx} D_{D/c}(z) \\ z &= \frac{x_F}{x} \,. \end{aligned} \tag{9}$$

We use the Peterson fragmentation function,

$$D_{D/c}(z) = \frac{N}{z\left[1 - \frac{1}{z} - \frac{\epsilon}{1-z}\right]^2}. \tag{10}$$

Inclusion of Next to Leading Order (NLO) contributions into the D-meson cross section does not produce appreciable changes neither in the form of the D-meson distribution or in its normalization (see e.g. [8]). At NLO the cross section for the production of an anti-quark differs from the cross section for the production of a quark, but this effect is small [8].

3 Light quark corrections to charm photoproduction

We will identify the hadron like part of the photon with ρ and ω vector mesons neglecting the contribution of heavier resonances which have smaller couplings to the photon. The ρ and the ω can be regarded as two states systems

$$\rho^0 = \frac{1}{\sqrt{2}}\left(u\bar{u} + d\bar{d}\right); \quad \omega = \tfrac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right). \tag{11}$$

$$\tag{12}$$

The photoproduction of D mesons may take place by QCD interaction of the vector meson V with the proton and/or by recombination of its constituent quarks (see Fig. 2). Therefore, in obtaining the differential cross section of the process $Vp \to DX$, we will consider two possible processes,

$$\frac{d\sigma}{dx_F}(Vp \to DX) = \frac{d\sigma_{VDM}^{qcd}}{dx_F}(Vp \to DX) + \frac{d\sigma_{VDM}^{rec}}{dx_F}(Vp \to DX). \tag{13}$$

In order to calculate these two contributions to the total cross section, we assume that the momenta distribution of the quarks of a ρ, ω meson are the same than inside a pion. We will use the GRV parametrization for the parton distribution in the pion.

3.1 QCD resolved photon contribution

The photon may interact through ist constituents with the partons in the proton. In the parton fusion mechanism, $D^{\pm}$ $D^0(\bar{D}^0)$ mesons could be produced via the $q\bar{q}(gg) \rightarrow c\bar{c}$ with the subsequent fragmentation of the $c(\bar{c})$ quark. The contribution of the hadronic (or resolved) component of the photon is given by the usual formula that describes hadron-hadron interactions,

$$\frac{d\sigma^{qcd}_{VDM}}{dx_F} = \frac{\sqrt{s}}{2} \sum_{i,j} \int dp_T^2 dy_4 \frac{x_1 f_i(x_1,\mu) x_2 f_j(x_2,\mu)}{E} \frac{d\hat{\sigma}}{d\hat{t}} \frac{D_{D/c}\left(z\right)}{z} \tag{14}$$

where $x_1 f_i(x_1, \mu^2)$ is the parton distribution in the resolved photon, $x_2 f_i(x_2, \mu^2)$ is the parton distribution in the proton, E is the energy of the fragmenting charm quark and $D_{D/c}(z)$ is the fragmentation function.

The partonic cross section in Eq. 14 is given by

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\pi \alpha_s^2(\mu)}{\hat{s}^2} \left[\overline{\sum} \mid M_{i,j} \mid^2_{q\bar{q}} + \overline{\sum} \mid M_{i,j} \mid^2_{gg} \right] \tag{15}$$

with the invariant matrix elements squared and averaged (summed) over initial (final) colours and spins at LO in pQCD given by

$$\begin{aligned}
\overline{\sum_{q\bar{q}\rightarrow c\bar{c}}} \mid M_{i,j} \mid^2 &= \frac{4}{9} \frac{\left(\hat{t}-m_c^2\right)^2 + \left(\hat{u}-m_c^2\right)^2 + 2m_c^2\hat{s}}{\hat{s}^2} \\
\overline{\sum_{gg\rightarrow c\bar{c}}} \mid M_{i,j} \mid^2 &= 12 \frac{\left(m_c^2-\hat{t}\right)\left(m_c^2-\hat{u}\right)}{\hat{s}^2} + \frac{8}{3} \frac{\left(m_c^2-\hat{t}\right)\left(m_c^2-\hat{u}\right) - 2m_c^2\left(m_c^2+\hat{t}\right)}{\left(m_c^2-\hat{t}\right)^2} \\
&+ \frac{8}{3} \frac{\left(m_c^2-\hat{t}\right)\left(m_c^2-\hat{u}\right) - 2m_c^2\left(m_c^2+\hat{u}\right)}{\left(m_c^2-\hat{u}\right)^2} - \frac{2}{3} \frac{m_c^2\left(\hat{s}-4m_c^2\right)}{\left(m_c^2-\hat{t}\right)\left(m_c^2-\hat{u}\right)} \\
&- 6 \frac{\left(m_c^2-\hat{t}\right)\left(m_c^2-\hat{u}\right) + m_c^2\left(\hat{u}-\hat{t}\right)}{\hat{s}\left(m_c^2-\hat{t}^2\right)} \\
&- 6 \frac{\left(m_c^2-\hat{t}\right)\left(m_c^2-\hat{u}\right) + m_c^2\left(\hat{t}-\hat{u}\right)}{\hat{s}\left(m_c^2-\hat{u}^2\right)} .
\end{aligned} \tag{16}$$

Writing the four momentum of the incoming and outgoing particles as

$$\begin{aligned}
p_1 &= \frac{\sqrt{S}}{2} \left(x_1, 0, 0, x_1\right) \\
p_2 &= \frac{\sqrt{S}}{2} \left(x_2, 0, 0, -x_2\right) \\
p_c &= \left(m_T \cosh(y_c), p_T, 0, m_T \sinh(y_c)\right) \\
p_{\bar{c}} &= \left(m_T \cosh(y_{\bar{c}}), -p_T, 0, m_T \sinh(y_{\bar{c}})\right) \ ,
\end{aligned} \tag{17}$$

the Mandelstam variables appearing in Eqs. 16 are given by

$$\begin{aligned}
\hat{s} &= 2m_T^2\left(1+\cosh(\Delta y)\right) \\
\hat{t} &= m_c^2 - m_T^2\left(1+\exp(-\Delta y)\right) \\
\hat{u} &= m_c^2 - m_T^2\left(1+\exp(\Delta y)\right) \\
\Delta y &= y_c - y_{\bar{c}}.
\end{aligned} \tag{18}$$

In our calculation we use the GRV-LO [7] parton distributions in protons and pions, and apply a global factor of $2-3$ in order to account for NLO effects. For the fragmentation function we use the Peterson function.

3.2 Charmed meson production by recombination

In the scenario described in [9] for π^- proton collisions, the annihilation of a u quark from the proton and the $\bar{u}$ quark in the pion would liberate the d of the pion which in turn recombines to form a D^- and certainly not a D^+. On a similar base a ρ^0 proton collision will favor the production of $\bar{D}^0$ and D^- over D^0 and D^+ depending on the quantum state of the colliding ρ^0 at the interaction point (see Fig. 3).

The production of leading mesons at low p_T was described by recombination of quarks long time ago [10]. In recombination models one assumes that the outgoing hadron is produced in the beam fragmentation region through the recombination of the maximum number of valence quarks and the minimum number of sea quarks of the incoming hadron. The invariant inclusive x_F distribution for leading mesons is given by

$$\frac{2E}{\sqrt{s}\sigma}\frac{d\sigma^{rec}}{dx_F} = \int_0^{x_F}\frac{dx_1}{x_1}\frac{dx_2}{x_2}F_2\left(x_1,x_2\right)R_2\left(x_1,x_2,x_F\right) \tag{19}$$

where x_1, x_2 are the momentum fractions and $F_2\left(x_1,x_2\right)$ is the two-quark distribution function of the incident hadron. $R_2(x_1,x_2,x_F)$ is the two-quark recombination function.
The two-quark distribution function is parametrized in terms of the single quark distributions. For recombination of D^-, D^0

$$F_2\left(x_1,x_2\right) = \beta F_{d,u;val}\left(x_1\right)F_{\bar{c};sea}\left(x_2\right)\left(1-x_1-x_2\right), \tag{20}$$

with $F_q\left(x_i\right) = x_i q\left(x_i\right)$. We use the GRV-LO parametrization for the single quark distributions in Eq. 20. It must be noted that since the GRV-LO [7] distributions are functions of x and Q^2, our $F_2\left(x_1,x_2\right)$ also depends on Q^2.
The recombination function is given by

$$R_2\left(x_{u,d},x_{\bar{c}}\right) = \alpha\frac{x_{u,d}x_{\bar{c}}}{x_F^2}\delta\left(x_{u,d}+x_{\bar{c}}-x_F\right)\ , \tag{21}$$

with α fixed by the condition $\int_0^1 dx_F (1/\sigma) d\sigma^{rec}/dx_F = 1$.
Some time ago V. Barger *et al.* [11] explained the spectrum enhancement at high x_F in Λ_c production assuming a hard momentum distribution of charm in the proton. Here we will also take a QCD evolved charm distribution, of the form proposed by V. Barger *et al.* [11]

$$xc(x, \langle Q^2 \rangle) = N x^l (1-x)^k, \tag{22}$$

with a normalization N fixed to

$$\int dx \cdot xc(x) = 0.005 \tag{23}$$

and $l = k = 1$. With this values for l and k one tries to resemble the distribution of valence quarks. In contrast with the parton fusion calculation, in which the scale Q^2 of the interaction is fixed at the vertices of the appropriated Feynman diagrams, in recombination the value of the parameter Q^2 should be used to give adequately the content of the recombining quarks in the initial hadron. We used $Q^2 = 4m_c^2$.

4 $D^{\pm}$ and $D^0(\bar{D}^0)$ total production

The inclusive production cross section of a D meson is then obtained by adding the contribution of recombination, Eq. 19, to the QCD processes from direct photon-gluon interaction, quark anti-quark annihilation and gluon-gluon fusion from the hadronic component of the photon, *i. e.*

$$\frac{d\sigma^{tot}(D^-)}{dx_F} = N_1 \left(\frac{d\sigma^{\gamma g}}{dx_F} + a \left(b \frac{d\sigma^{qcd}_{VDM}}{dx_F} + c \frac{d\sigma^{rec}_{VDM}}{dx_F} \right) \right) \tag{24}$$

$$\frac{d\sigma^{tot}(D^+)}{dx_F} = N_2 \left(\frac{d\sigma^{\gamma g}}{dx_F} + a \left(b \frac{d\sigma^{qcd}_{VDM}}{dx_F} + d \frac{d\sigma^{rec}_{VDM}}{dx_F} \right) \right) \tag{25}$$

with

$$\frac{d\sigma^{qcd}_{VDM}}{dx_F} = \frac{d\sigma^{gg}}{dx_F} + \frac{d\sigma^{q\bar{q}}}{dx_F} \tag{26}$$

and $N_1 = \frac{1}{1+ab+ac}$, $N_2 = \frac{1}{1+ab+ad}$ the parameters a, b, c and d depend on the contribution of each process to the total cross section. They are fixed in such a way that the differential cross section is well described, before calculating the asymmetry. The resulting inclusive D production cross section $d\sigma^{tot}/dx_F$ (shown in Fig. 4), is used then to construct the asymmetry defined in Eq. 1.
The values obtained for the different contributions in Eqs. 24 and 25 are in reasonable agreement with what one would expect. The photon fluctuation to a vector meson is of the oder of 1 %. Approximately 96 % of the total cross section comes from the photon gluon process. The contribution due to recombination goes from about 1 % (for D^-) to about 3 %

(for D^+). Fig. 5 shows the model prediction for the D^-, D^+ production asymmetry together with the experimental results from the E687 Collaboration [1]. The two curves correspond to the conventional GRV function distribution in the resolved photon and to the distribution proposed by Barger, *et al.* where a hard charm component has been assumed.

5 Conclusions

In an earlier work [12] the production asymmetry of Λ_c was described using the same recombination scheme used here. In hadroproduction the presence of a diquark in the initial state, plays an important role in Λ_c production. In photo production, however, the production mechanism is somewhat different and the asymmetry is much smaller. The parameters used here are in reasonable agreement with what is physically expected and with the values used in a previous study of production asymmetries in π proton collisions [4]. Changing the values of these parameters may improve the description of the asymmetry but then they may loose meaning in the frame of the asymmetry obtained for hadro production.

Other experimental results for the asymmetry defined as:

$$A(x_F) = \frac{\sigma(D^+) - \sigma(D^-)}{\sigma(D^+) + \sigma(D^-)} \tag{27}$$

are $A = -0.0384 \pm 0.0096$ in $x_F \geq 0.0$ at photon energies of 200 GeV [1] and $A = -0.0196 \pm 0.0147$ in $x_F \geq 0.2$ at photon energies of 80-230 GeV, average energy 145 GeV [13]. The NA14 collaboration studied the asymmetry

$$A(x_F) = \frac{\sigma(D^+ + D^0) - \sigma(D^- + \bar{D}^0)}{\sigma(D^+ + D^0) + \sigma(D^- + \bar{D}^0)} \tag{28}$$

and obtained $A = -0.03 \pm 0.05$ $x_F \geq 0.0$ at photon energies of 40-140 GeV and 100 GeV in average [14].
All these results are in good agreement with each other but, the statistical errors are still large.

In ref. [1] experimental data are compared to a model based on string fragmentation. This model gives a larger asymmetry than the one obtained in our approach. The description obtained there is in much better agreement with the experimental results. However, more precise measurements are needed before one can draw a final answer.

One would expect that with increasing energy the resolved photon component increases giving rise to a larger contribution of the recombination mechanism which in turn would produce a larger production asymmetry. The HERA experiments should therefore be able to see a production asymmetry. However larger energies of the photon means also smaller values of x for the quarks that participate in the interaction and the hard charm component

is expected to play a minor role at small x's. *i e.*, the asymmetry should look rather as the one obtained from conventional densities. New experiments will have soon more precise measurements of the asymmetries. This new results will give us a better understanding of the underlying production mechanisms.

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Figure Captions

Fig. 1: According with perturbative QCD, photon-gluon fusion is the main process in charm photo-production.

Fig. 2: The resolved photon may interact with the proton via QCD, i.e. quark-antiquark annihilation and gluon-gluon fusion as shown in (a,b). A non perturbative interaction (c) may favor charm over anti-charm mesons production.

Fig. 3: After a fluctuation of the photon to a ρ^0 vector meson, the interaction with the proton may ocurr in one of the two states. In any case the valence quark in the ρ would be released once the antiquark annihilates with a quark of the proton.

Fig. 4: Total cross section as a function of x_F. Experimental results from [13] and theoretical calculation as in Eqs. 24 and 25 using the GRV distributions.

Fig. 5: Measured production asymmetry for D^- and D^+ from [1]. The curves show the model result in which a hard charm component (dashed line) and GRV-LO (solid line) in the pion has been considered. The horizontal line at $A(x_F) = 0$ is for reference only.

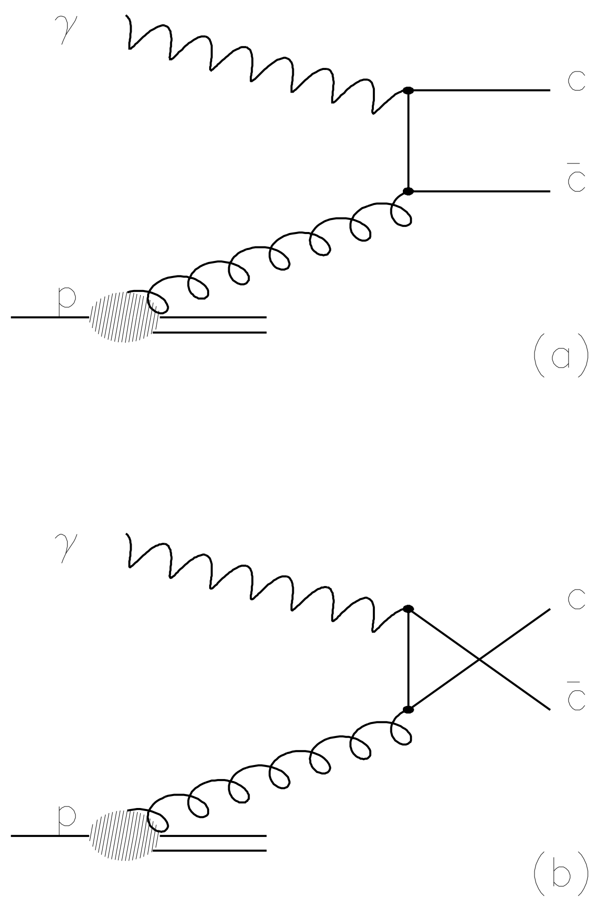


Figure 1:

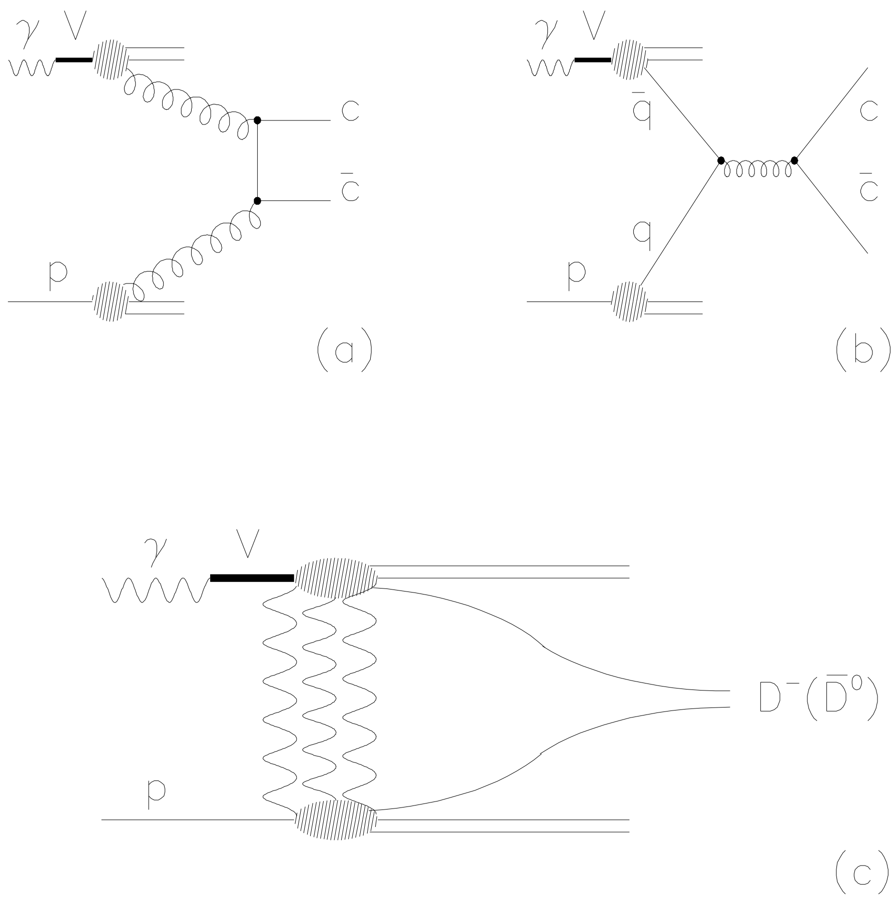


Figure 2:

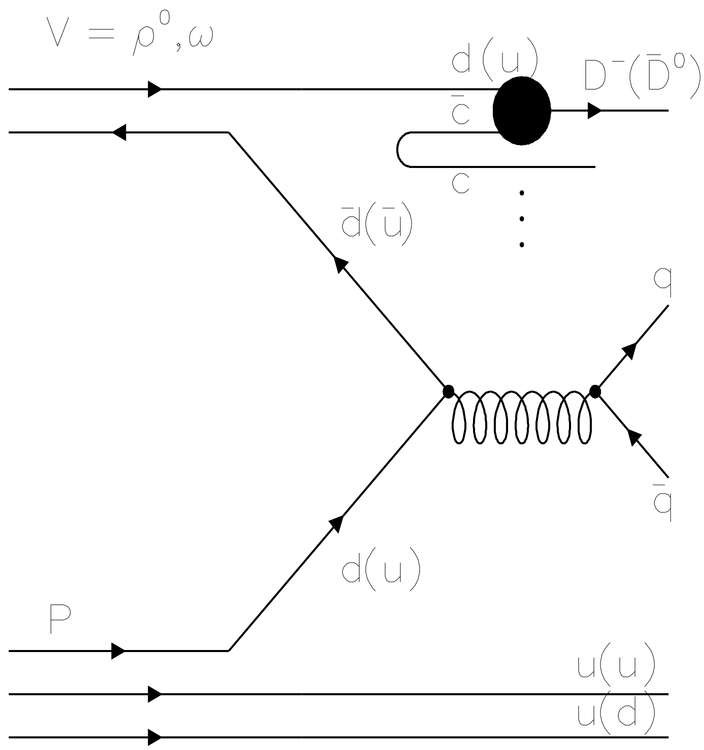
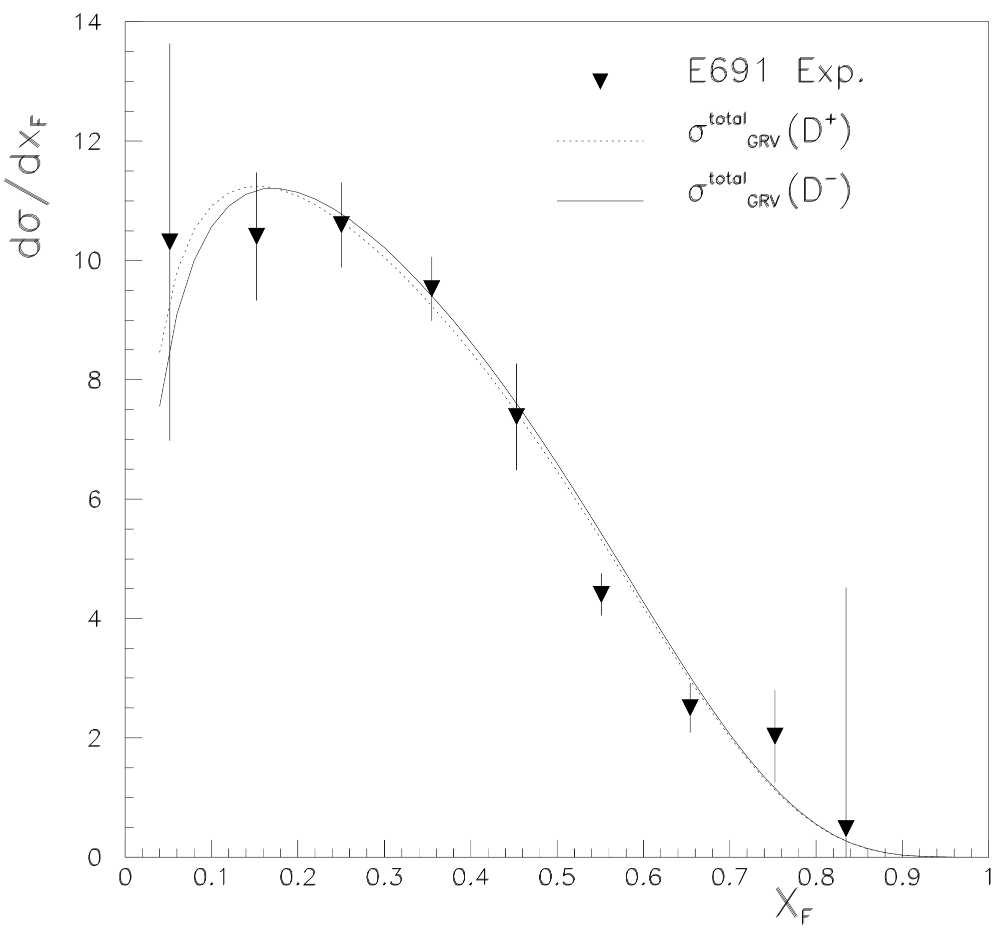


Figure 3:



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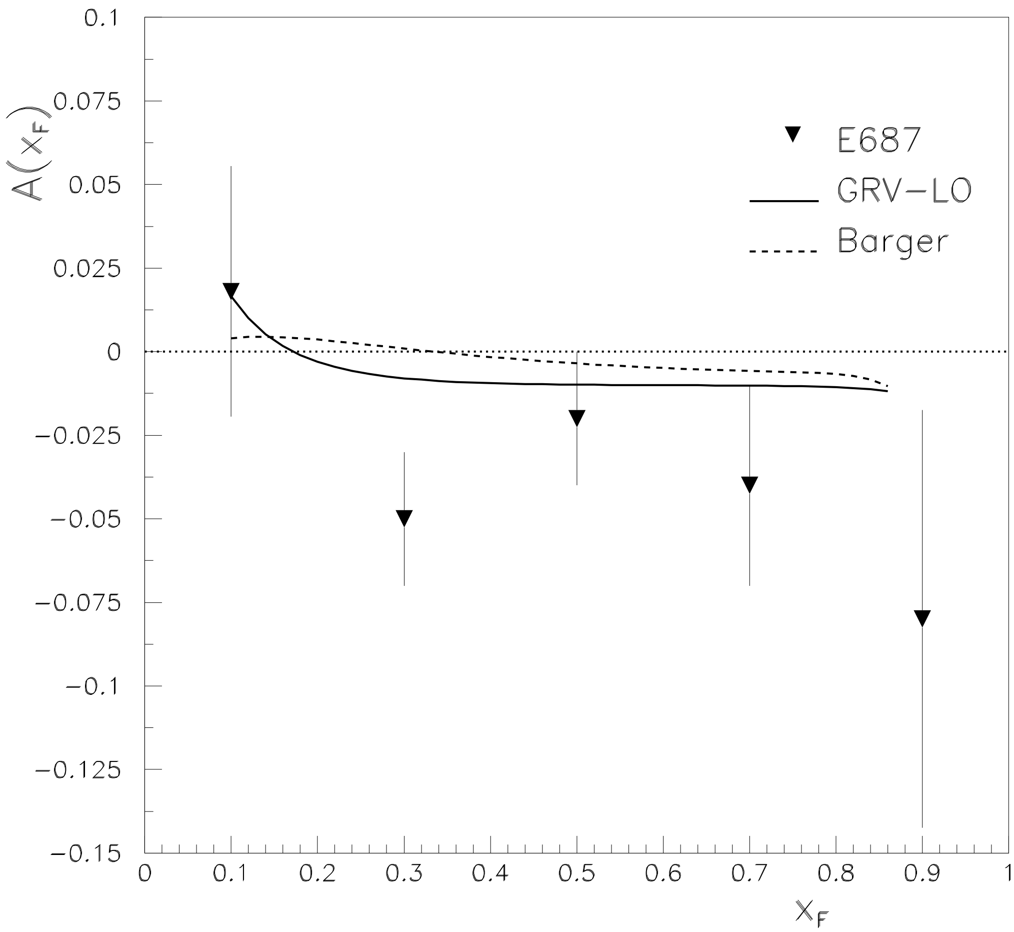
0.1
0.075
0.05
0.025
0
−0.025
−0.05
−0.075
−0.1
−0.125
−0.15
A(x_F)
E687
GRV−LO
Barger
0
0.1
0.2
0.3
0.4
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0.7
0.8
0.9
1
x_F

Figure 5: